523

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HIGH LATITUDE ASPECTS OF A DIFFERENTIAL GPS AIRCRAFT LANDING SYSTEM

by

James R. Clynch

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13. ABSTRACT *(maximum 200 words)* The use of differential Global Positioning System (DGPS) in an aircraft landing system at high latitude has been investigated. Both the effects of the high latitude on geometry and accuracy and the effects of scintillations on availability have been studied. Data was taken at McMurdo, and South Pole station, Antarctica over a two year period. It was found that commercially available systems should meet the FAA requirements for Special Category I landing systems in Antarctica.

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ABSTRACT

The use of differential Global Positioning System (DGPS) in an aircraft landing system at high latitudes has been investigated. Both the effects of the high latitude on geometry and accuracy and the effects of scintillations on availability have been studied. Data was taken at McMurdo and South Pole station, Antarctica over a two year period. It was found that commercially available systems should meet the FAA requirements for Special Category I landing systems in Antarctica.

TABLE OF CONTENTS

HIGH LATITUDE ASPECTS OF A
DIFFERENTIAL GPS AIRCRAFT LANDING SYSTEM

I.   INTRODUCTION

A.   Purpose

The aircraft landing system at the US bases in Antarctica must be replaced in the next few years. Differential Global Positioning System (DGPS) navigation has been identified as a prime candidate for this function.   This choice is based on technical and operational aspects of such a system. In addition during the last year, the US Federal Aviation Agency (FAA) has investigated the use of DGPS for the category I landing function and has had a specification [1] prepared for special use airfields. The FAA is also moving forward on the use of DGPS for public carriers. This interest ensures that multiple vendors will have equipment for DGPS aircraft landing systems available when needed for the Antarctic application.

There are however several unique features to operations in Antarctica.   It was felt that these should be investigated to determine if they were a problem and if so what remedial measures would be necessary.   There are two problems that needed to be investigated:

1. accuracy problems due to unique station satellite geometry at high latitudes,

2. potential signal outages due scintillation in high latitudes.

It was the purpose of this study to investigate these two items and acquire the data necessary to adequately specify a system that will function in Antarctica. In particular operations at McMurdo and South Pole station need to be supported and were the focus of this study.

B.   Method of Study

In order to address these two issues, the Naval Postgraduate School (NPS) put together an experiment and fielded it to McMurdo in January 1992. The equipment consisted of two GPS receivers and a data logging computer. It simulated a DGPS system with one receiver serving as a base station and the second as a remote. In this study, data were acquired on the accuracy of a DGPS system at the same time as the frequency of occurrence of scintillation problems was measured.

During 1992 the US Geological Study (USGS) operated a similar receiver at South Pole station. USGS provided those data to NPS in

order to address the scintillation problem at South Pole station. A NPS computer and data logging program were used during 1993 to collect similar scintillation data at the Pole as was done at McMurdo during 1992 in a cooperative effort between USGS and NPS.

C.   General Results

It was not expected that scintillations would be a problem in Antarctica [2]. These effects scale with the carrier frequency to the -3/2 power [3] and from comparison with 250 MHz data taken in northern polar regions [4] it seemed unlikely that scintillation would be a major cause of signal loss. This proved true at McMurdo. However, there were a few scintillation problems at Pole station. These problems were associated with very intense geomagnetic storms.

If aircraft receivers are used that track 9 or more satellites then the loss of lock on a few satellites should not be a major problem. However the FAA standard [1] requires only a minimum of 6 tracking channels in an aircraft receiver. This is one issue where the specification for an Antarctic system will have to exceed those for use only in the US. It is expected that more than one vendor will offer receivers with 9 or more channels.

The accuracy of the system provided no surprises. Because the satellites are at a 55 deg inclination, they never come overhead in

Antarctica, which is at latitudes higher than 55 deg. The lack of very high elevation angle satellites makes for a poorer determination of altitude, the key quantity in an aircraft landing system. However there are always many satellites visible, with the average being about 7.5 in McMurdo and 8.5 at Pole. This somewhat negates this problem.

A model was developed for the error in the differential GPS system. This was a simple extension of the standard dilution of precision model [5]. A scale constant was added to account for the effects of multipath. The measured averages and detailed probability distribution of the errors at McMurdo fit this model very well. Based on this model, which has satellite geometry, ground receiver noise, aircraft receiver noise, and the multipath factor as inputs, current receivers can meet the accuracy part of the FAA proposed specification [1] in Antarctica.

II. BACKGROUND

A. Global Position System and Differential Operations

The Global Positioning System (GPS) is a satellite based navigation system operated by the US Department of Defense (DoD). This system has several levels of accessibility. The lowest level is available to the public and has been guaranteed to be maintained at its nominal level for 15 years for the purpose of air traffic navigation. This provides a real time position anywhere, anytime at a 100 m horizontal and 150 m vertical, at a 95 % confidence level.

In GPS navigation the user receives signals from 4 or more GPS satellites at the same time. There are 24 satellites in very high orbits that ensure that sufficient satellites are available above the horizon at all times. Modern GPS receivers observe more than the 4 satellites necessary for a minimal solution. This improves the accuracy of the solution and allows for autonomous detection of bad satellite signals. This is called Receiver Autonomous Integrity Monitoring (RAIM). If 6 satellites are observed, in addition to determining that something is wrong, the satellite in error can be identified. The FAA proposed specification, called the MASP [1], specifies a 6 channel receiver with RAIM.

While 100 to 150 m is adequate for en route navigation, it is not accurate enough for a landing system. For example, Category I landings require a total system error in the vertical of 9.6 m 95% of the time (4.8 m one standard deviation). This is the total system error. For Category I landing systems, 4.3 m of the 4.8 m is allocated to the sensor error. Fortunately there is a method of achieving this with GPS.

Almost all of the errors in the solution are due to systematic errors on the satellite signals. These errors vary slowly over space and will be essentially identical for two receivers separated up to several hundred km. Therefore one only has to deploy a receiver to a fixed know location, measure the errors in real time, and broadcast them to nearby operators. This is called differential GPS (DGPS). It is so useful that there has been a standard for the broadcast of the corrections for over 5 years. The US Coast Guard is implementing DGPS for ship navigation on all US coast lines and the great lakes. This is also the technique that the FAA is specifying for Category I landing systems [1].

A typical DGPS landing system is diagramed in Fig 1. Here there are three GPS receivers. In a flight critical system there must be monitoring to ensure the correctness (Integrity) of signals. A primary ground reference system receives the GPS signals and generates corrections. These are formatted and broadcast. They are received by the user, here an aircraft. The
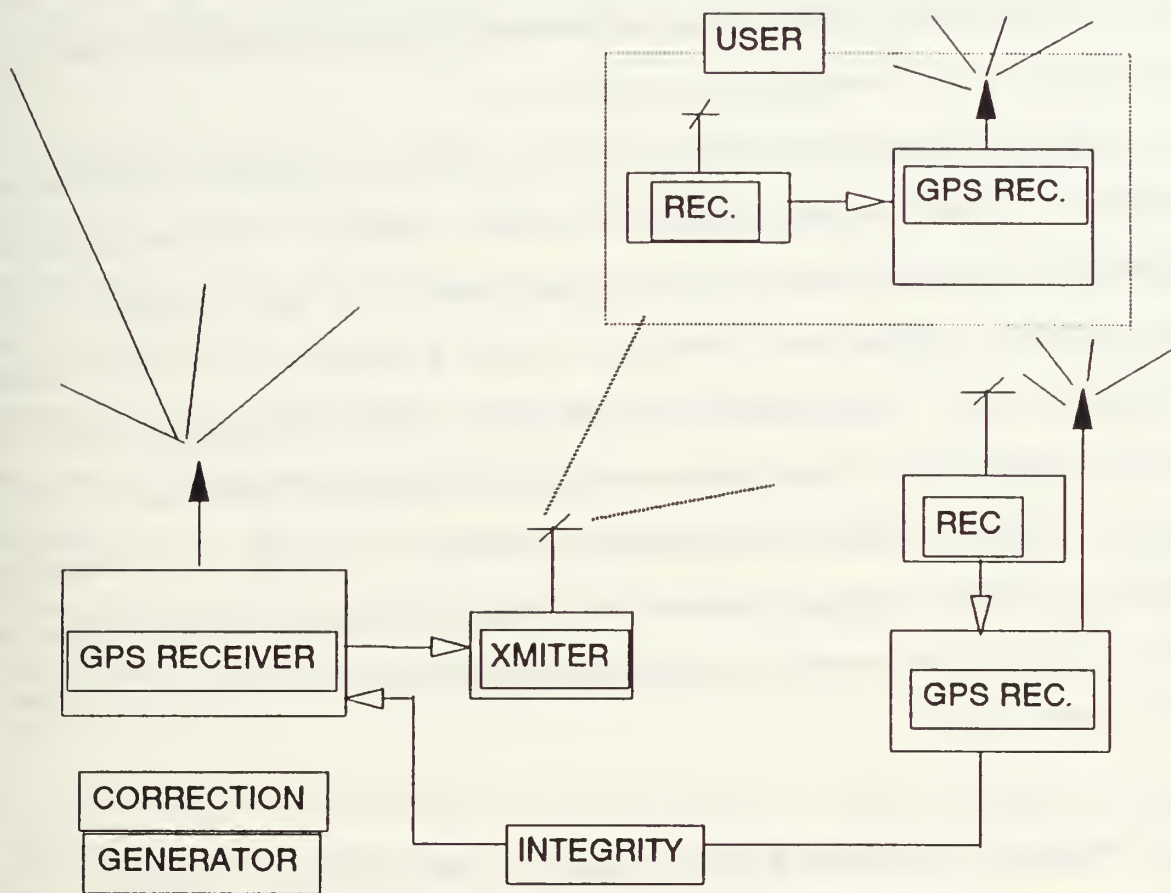
Figure 1

Typical Special Category I Landing
System Configuration

user also receives the GPS signals, which it corrects with the reference signal.   A second system, at a fixed known location performs a similar function.   Because its location is known it can determine the error in the reference station corrections.   If they fall out of tolerance, it sends a message, via hardwired connection to the reference station to set error flags for user aircraft. This is called the integrity monitor.

The accuracy of GPS and DGPS system is typically spoken of in terms of Dilution of Precision (DOP) values.   In general it is assumed that the error in a component is the product of the measurement noise and the DOP.   For altitude, or the vertical component, this is the VDOP. In general there are enough satellites at both stations to provide the MASP suggested VDOP of 4 all the time.   With a lower noise ground station VDOPs of 6 should be usable.   These are available in Antarctica most of the time even with one or two satellites unavailable due to scintillations or other problems.

One way to dramatically improve the vertical accuracy is to have a pseudo satellite (pseudolite) at the station.   This is a stationary, low power transmitter that transmits a signal in the same format as a GPS satellite.   The main reason that vertical is the least well determined coordinate is that all satellites are on one side, above, the user.   A pseudolite removes this asymmetry. A study was done that showed that a pseudolite, even one on a hill at McMurdo greatly improved the situation through a lowering of the

8

VDOP. However, other parts of this study have shown that minimum Category I standards can be met without this extra piece of hardware. Pseudolites will not be considered further in this study.

B.   High Latitude Ionospheric Scintillations

Signals observed on or near the earth from satellites must go through a region where there are significant free ions and electrons. This is called the ionosphere and extends from about 100 km to 1000 km in altitude. It is important because the electrons can modify the path of radio signals. This effect is frequency dependent and falls off as one over the square of the frequency. At HF (5 - 30 Mhz) this can totally reflect signals making long distance HF communications possible. GPS signals are at 1575 Mhz are only slightly effected.

If there is turbulence in the electrons with spatial changes on the order of a wavelength, significant scattering occurs. This causes signals to vary in intensity and phase, a phenomena called scintillation. This is a significant problem at VHF, but falls off with frequency as the -3/2 power. At GPS frequencies it should not be a significant problem in polar regions.

It should be noted that there are two regions that produce ionospheric scintillations, the polar regions and the equatorial

regions [2]. The physical mechanisms are totally different and the scintillations in the equatorial region can be more intense than those in the polar region [2,6]. Therefore one must be careful about general statements about "ionospheric scintillation" and determine is the statements apply to both regions or only one.

The earth's magnetic field shields the earth from high energy particle streams coming from the sun. It does this by deflecting the particles into paths that follow field lines. This means that the particles hit the upper atmosphere in the polar regions, where these field line intersect the 100 - 400 km altitude they deposit energy and cause turbulence. This is in an oval about 12 to 14 deg from the pole. However this is the magnetic pole, which is offset from the spin axis by about 12 deg. This circle is called the auroral oval because it is where this interaction causes optical emissions (aurora).

The structures that cause the scattering are highly aligned with the earth's magnetic field in polar regions. Therefore the scattering is most intense when the line of sight to the satellite is near to the magnetic field lines at altitudes of about 300 km. This condition is never met for GPS satellites at McMurdo which is quite near the south magnetic pole. At South Pole station, which is in the southern auroral oval the alignment is high, but not close to parallel for GPS satellites.

High latitude scintillations occur in the auroral oval and over a slightly wider region. Polar scintillations and aurora are both caused by solar emissions that vary significantly with the 11 year solar cycle. There are very few events during solar minimum and more during solar maximum. The last maximum occurred in 1990-91 and the next will occur in 2001-2002. The solar activity is usually quantified by the monthly Zurich sun spot number (Rz). This is shown over the last decade in Fig 2. The last maximum was broader than usual and lower than some. Cycles tend to alternate between small and large maximum intensity. The last one was in the middle however.

Associated with these events are also variations in the earth's magnetic field. These aren't large compared to the ambient field, but can be easily measured. Therefore these events are called geomagnetic storms. The perturbation in the magnetic field is measured by several numbers. The planetary K-index (Kp) is a logarithmic scale. Upon converting it to a linear scale it is called Ap. Ap is plotted for the last decade in Fig 3. It has clear isolated spikes, the geomagnetic storms. The highest activity is during solar maximum, but isolated storms do occur during low solar activity. There were two very intense or "great" storms last cycle, one in 1989 and the other in 1986 during low solar activity. During these very intense storms, aurora can be

MONTHLY SOLAR ACTIVITY
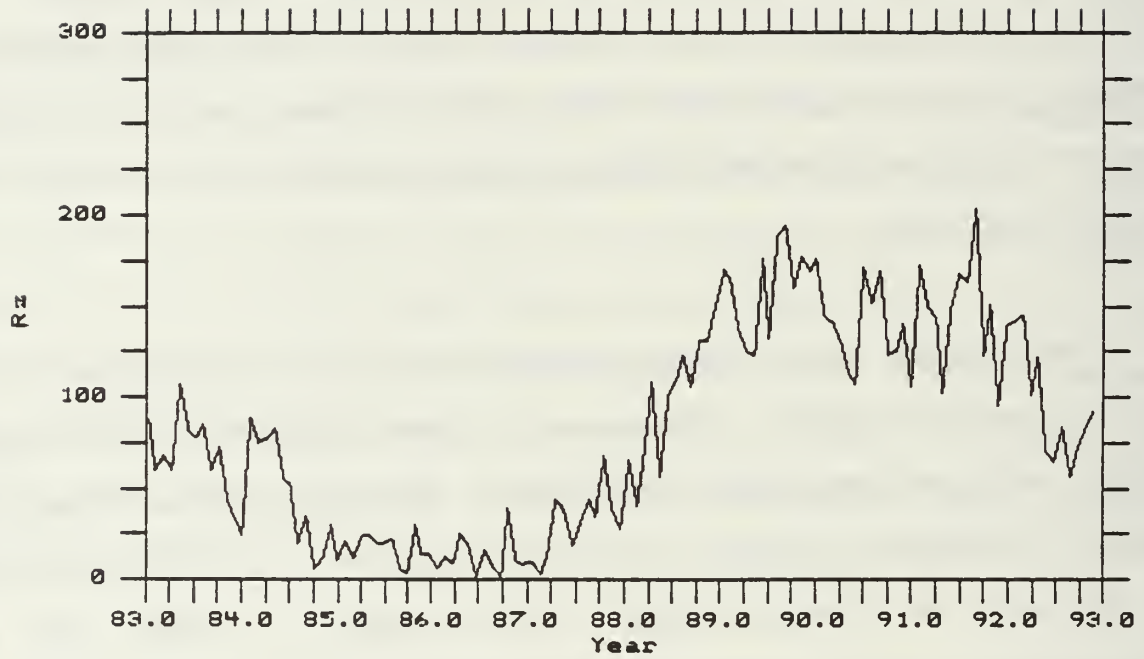
Figure 2
Mean Monthly Solar Activity
Sunspot Number

12

DAILY AVERAGE MAGNETIC ACTIVITY
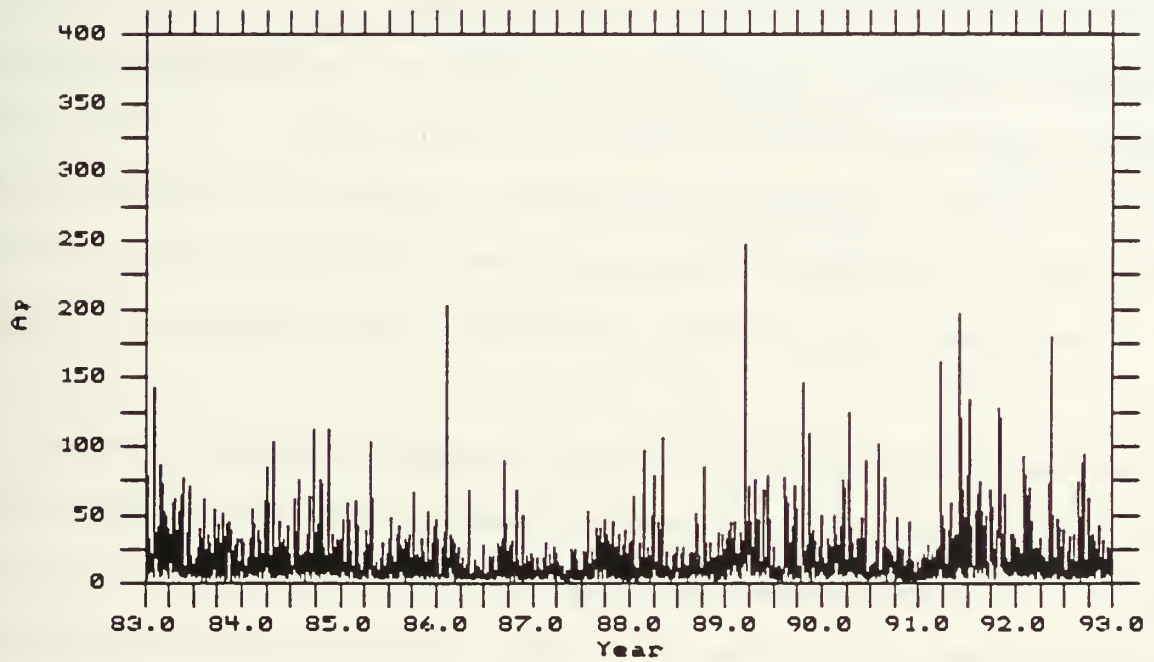
Figure 3
Magnetic Activity Daily Averaged Ap

13

seen as far south as Mexico.

The experiment was rapidly developed and deployed to the field in order to catch as many magnetic storms as possible. It caught the Ap peak in mid 1992 (see Fig. 3) and the smaller peaks late in the year. It therefore caught one intense storm, two moderate storms, and no very intense storms.

III.   DESCRIPTION OF EXPERIMENT

A.   McMurdo 1992

In order to acquire data quickly, two geodetic GPS receivers, Ashtech MD XII's, were obtained from the Defense Mapping Agency and software developed to analyze data on the fly. A system diagram is shown in Fig. 4.   This looks very much like the standard landing system configuration without integrity monitoring. Because we are not using real aircraft, integrity was not necessary. In addition because we know where the sites are, errors can be measured.

The data logging computer accepts data from both receivers at a 1 Hz rate. It examines these on the fly, and determines if any satellite has changed status, (is missing for example). It logs all acquisitions and loss of signal. In addition it determines the position error and several other quantities. Averages of these quantities are computed over 5 minute windows and saved. For the position error the error distribution is also accumulated and saved.

An operational landing system will operate only on the signal called the L1 C/A (course acquisition). This is the signal available to the public and used by the USCG and the FAA. Even-

15

Reference Receiver   Corrections   Mobile Receiver

Data, Status   Data, Status

Logging PC

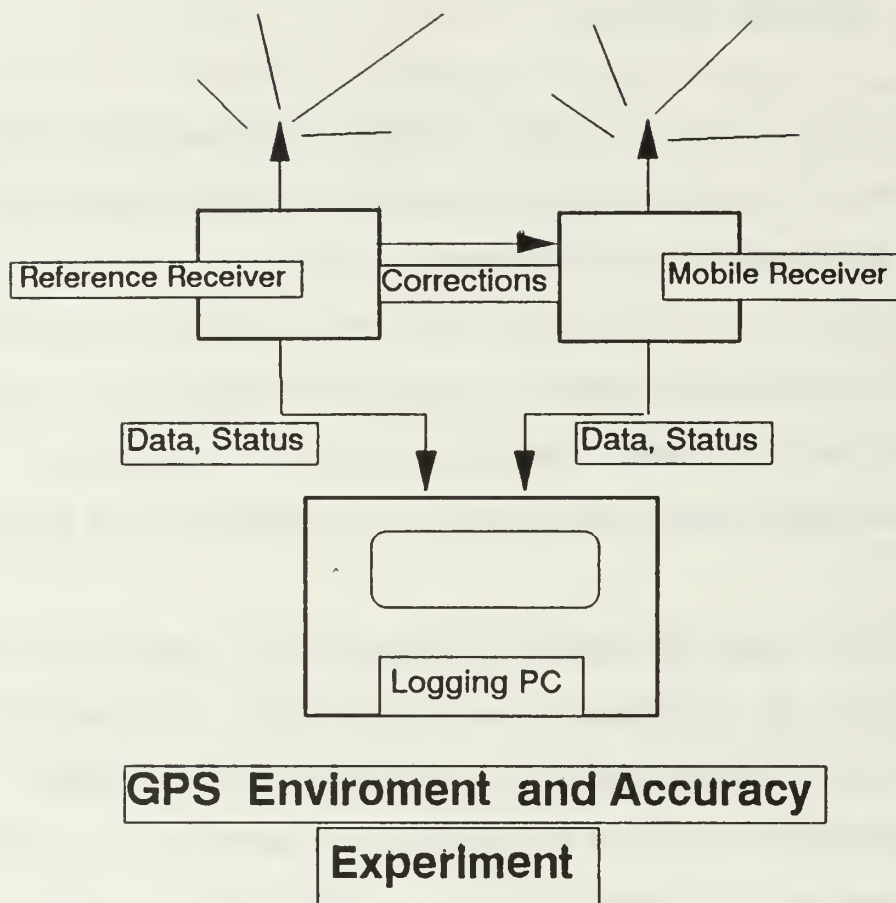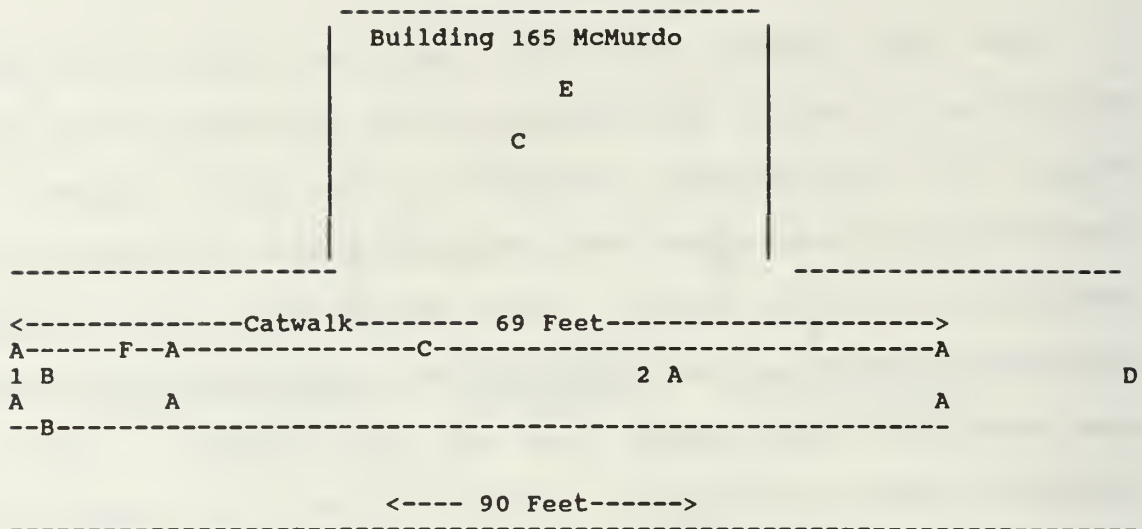GPS Enviroment and Accuracy
Experiment

Figure 4

though the receivers used could and did track other signals, only the values from the C/A signal was used in this study.

When the system was first deployed there were only 16 satellites in orbit. By the end of the year there were 19. This caused an unanticipated problem. The data logger or the communication line became overloaded and missed data when 9 or more satellites were in track. This caused some data processing problems as these bad data records were interpreted as missing and some satellites had false loss of locks logged. This became extensive late in the season. Therefore only data before day 200 1992 from McMurdo were used in analysis.

A second problem with the experiment was the location of the antenna. A diagram of the roof of the building where the McMurdo experiment was setup is shown in Fig 5. The locations of the GPS antennas ("1" and "2" in the diagram) are surrounded by many other antennas which served as multipath sources and in some directions blocked low elevation signals. This did not invalidate the data, but did point out the importance of having a good multipath free site for a ground reference system.

Starting at day 45 and extending until 200 1992, 154 days of data were acquired and used for analysis of accuracy and signal availability from this McMurdo site.

```
                    ---------------------------
                   |  Building 165 McMurdo     |
                   |                           |
                   |            E              |
                   |                           |
                   |            C              |
                   |                           |
                   |                           |
                   |                           |
                   |                           |
 ---------------------                          ---------------------

 <--------------Catwalk-------- 69 Feet--------------------->
 A-------F--A----------------------C-----------------------------------A
 1 B                                        2 A                        D
 A           A                                           A
 --B----------------------------------------------------------


                        <---- 90 Feet------>
 -----------------------------------------------------------------------

    LEGEND:
    1 & 2 Antenna locations for the GPS experiment
    A   VHF FM 138-156 MHz 25-30 Watts           Vertical
    B   Receive only 1265 KHz                    Directional
    C   Satcom antennas 248-310 MHz 50 Watts Circular Directional
    D   Satcom antenna 2273.5 MHz               Directional
    E   VHF FM 140-175 MHz 20 Watts             Vertical
    F   Satcom antenna 306.775 MHz 20 Watts  Half Omni (Circular Polarization)
```

Figure 5

McMurdo Experiment Environment
GPS Antennas at Locations 1 and 2

18

B. South Pole 1992

The USGS operated an Asthech P-XII receiver during 1992/3 at the South Pole station. They made their achieved data from 1992 available to NPS. This allowed for comparison of data taken at the same time at Pole and McMurdo. In addition it included three significant geomagnetic storms.

This data was analyzed to determine loss of locks. It did not have any data logging problems as it only recorded data at 30 sec intervals. However this means that the granularity of the results are in 30 sec steps. Because only one station was available, no DGPS accuracy values could be determined. The real time absolute positions had errors on the order of 100 m, as expected, and were not useful in this high accuracy study.

The South Pole site was on the top of the Skylab tower. It was felt to be fairly free of multipath objects. Though some multipath was detected in the data.

C. South Pole 1993

A modified version of the computer program that logged data at McMurdo during 1992 was run at Pole in 1993. It logged data at 30 sec epoch for USGS and analyzed 2 sec data on the fly for loss of lock studies.

IV. ACCURACY RESULTS

The error distributions were essentially those predicted by a covariance analysis using a 2 m system noise (1.4 m per receiver). For example the probability distribution in the over 500,000 points during the week beginning on day 124 1992 are shown in Fig 6. The two lines in the peak are for latitude and longitude. The lower curve is for height. As expected height is the worst coordinate due to the absence of very high elevation satellites. In the next figure (Fig. 7) is shown the prediction using the almanac for day 120 1992 using a system noise value of 2 m. The plots in Fig.'s 7 and 8 are essentially indistinguishable. This close fit of the measure error distributions to a simple model was true for all weeks.

The average noise needed to match the data was about three times the value measured in a laboratory environment. The rms error should be the product of the receiver noise and the DOP,

$$\sigma_M = \sqrt{\sigma_a^2 + \sigma_g^2} \qquad (1)$$

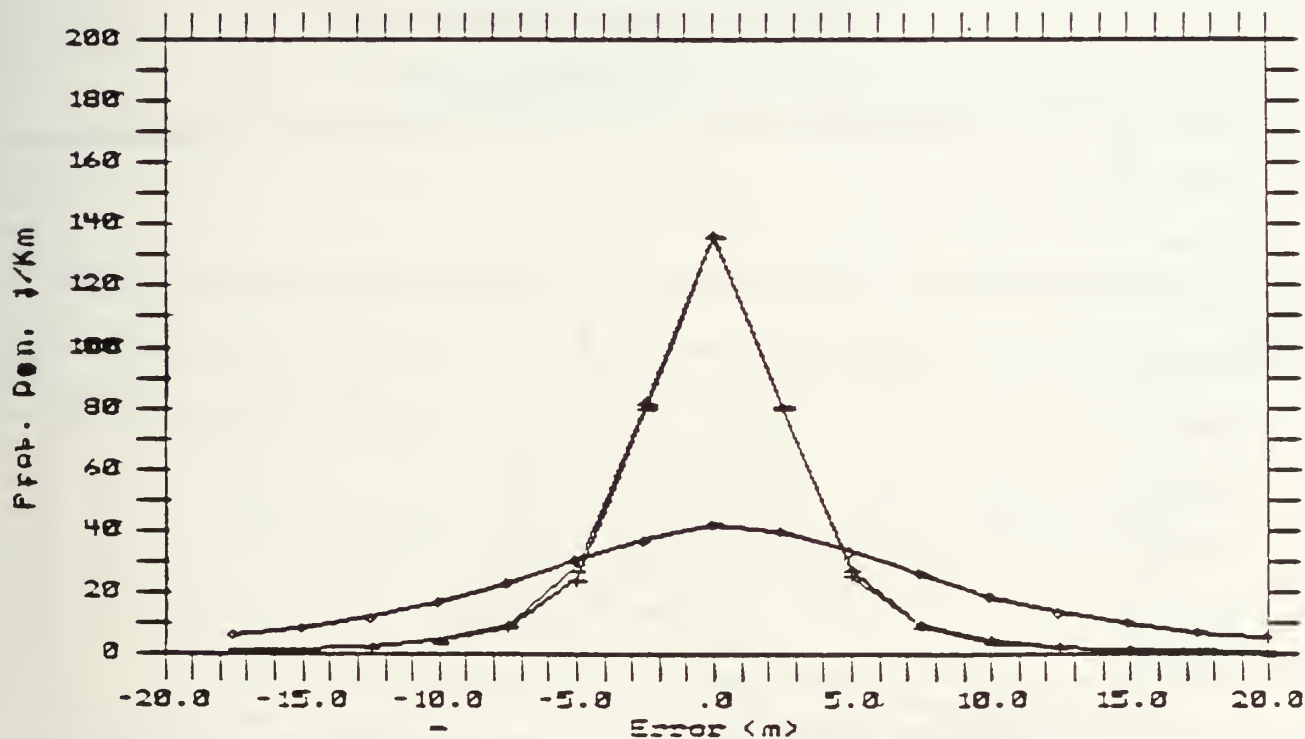$$\sigma_v = D_v \sigma_M \qquad (2)$$

where,

Figure 6
Measured Differential GPS Position
Error Distribution at McMurdo

Lower Curve Altitude, Upper Two
Latitude and Longitude
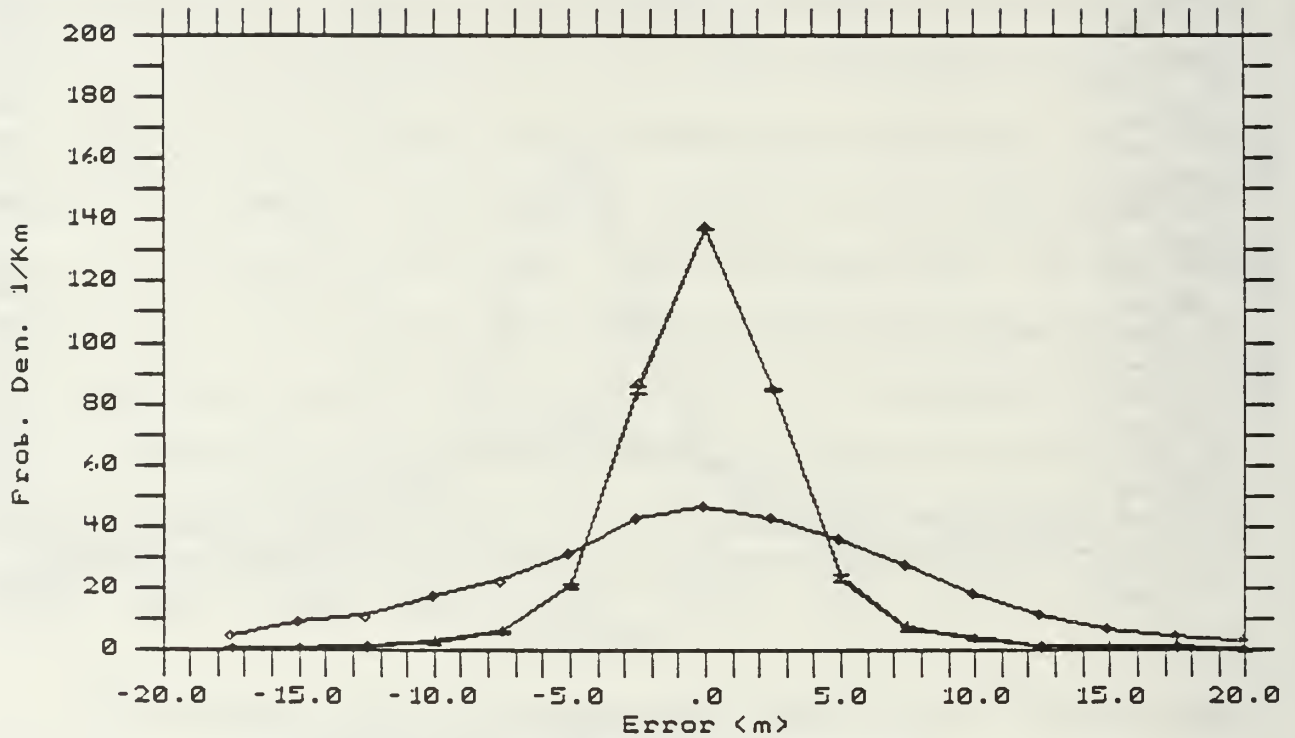
McMurdo Simulation 120 1992

2 m Measurement Noise

Figure 7
Model Differential GPS Position
Error Distribution at McMurdo

Lower Curve Altitude, Upper Two
Latitude and Longitude

22

σ_M is the differential system measurement noise,

σ_a is the aircraft measurement noise,

σ_g is the ground station measurement noise,

σ_v is the vertical solution noise, and

D_v is the VDOP.

According to simple theory [4] value of the vertical random error is just the product of the VDOP and the system measurement noise. Therefore the ratio,

$$M_f = \frac{\sigma_v}{D_v \sigma_M} \qquad (3)$$

should be constant at 1. It will be large in the real world due mainly to multipath effects. This therefore defines the multipath factor, M_f.

In the McMurdo experiment, the values of the VDOP and errors in each axis were averaged in real time over 5 min windows and recorded. The experimental ratio of average vertical error divided by average VDOP is plotted against time of day for 6 days beginning with day 131, 1992 in Fig 8. It is clear that this ratio varies a lot, but in a pattern that repeats, slightly earlier each

day. This is a signature for multipath. The geometry of the satellites repeats every 23 hr 56 min. Therefore multipath should repeat daily, only 4 min earlier each day. This is particularly evident in the area between 3 and 6 hrs UT in Fig. 8. The average value of this curve divided by the true σ_M (about 0.5 m for these receivers) is the multipath value for this site.

Another important result is illustrated by this Fig. 8. The most intense geomagnetic storm in our data sets occurred about 12 UT on day 131. This is not evident in this graph. The effects on the accuracy of the storm were not significant at McMurdo.

The following simple model fits the data well. The altitude error, averaged over a day, will be the product of the effective system noise, the VDOP, and a multipath factor. This implies that in high multipath environments the error distribution is normal with an effective measurement noise of the real value times a scale value. This is convenient for error analysis.

The Multipath factor must be at least 1, and will probably be 1.2 at lowest. For the McMurdo build 165 roof it was a horrible 3. This points out the importance of site selection for the ground station.

Today most older receivers have a receiver measurement noise of 0.5 m. There is a newer "narrow correlator" family of receivers
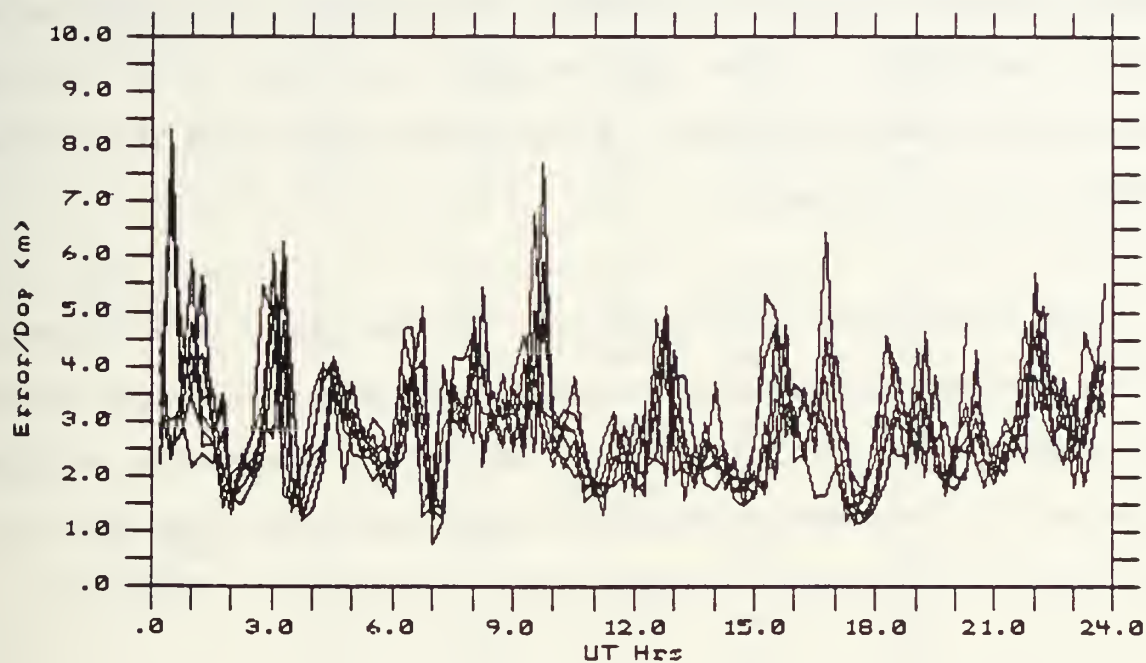
24

Figure 8
Multipath Factor For One Week at
McMurdo Showing 4 Min/Day Precision

25

that have noise values of 0.1 to 0.2 m. Using these values one can produce a table of expected vertical accuracy under various conditions. This is shown in Table I. Here two noise values have been used, a conservative 0.2 m for narrow correlator family, and 0.5 for the older generation. All combinations of airborne and ground receiver noises are present. In addition multipath factors of 1.2 (minimal in the real world), 2.0, and 3.0 (a high, unacceptable value) are used. Finally two often used VDOP values, 4.0 and 6.0 are present.

With a multipath factor of 1.2, the FAA limit is met with all but one combination of other factors. If only the ground station has a narrow correlator receiver, then with a reasonable multipath factor of 2.0 the system meets FAA specifications with VDOP of 4. For a very clean ground antenna site it passes for VDOP of 6.

The FAA has introduced the concept of the "Tunnel". This is a tunnel that is narrow at the decision height and wide at higher altitude. In effect one can proceed down the tunnel to a height where the predicted error exceeds the lower vertical boundary. For the 6.5 m sensor error values in Table I this altitude is 400 ft. This points up the importance of a clean reference antenna area.

Table I
Vertical Error Model Values
(1 Sigma)

	Grnd σ_g (m)	Air σ_a (m)	M_f	D_v VDOP	σ_v (m)	Meets FAA CAT I
N.C. Grnd	0.2	0.2	1.2	4.0	1.4	*
N.C. Air	0.2	0.2	2.0	4.0	2.3	*
	0.2	0.2	3.0	4.0	3.4	*
	0.2	0.2	1.2	6.0	2.0	*
	0.2	0.2	2.0	6.0	3.4	*
	0.2	0.2	3.0	6.0	5.1	
N.C. Grnd	0.2	0.5	1.2	4.0	2.6	*
S.C. Air	0.2	0.5	2.0	4.0	4.3	*
	0.2	0.5	3.0	4.0	6.5	
	0.2	0.5	1.2	6.0	3.9	*
	0.2	0.5	2.0	6.0	6.5	
	0.2	0.5	3.0	6.0	9.7	
S.C. Grnd	0.5	0.5	1.2	4.0	3.4	*
S.C. Air	0.5	0.5	2.0	4.0	5.7	
	0.5	0.5	3.0	4.0	8.5	
	0.5	0.5	1.2	6.0	5.1	
	0.5	0.5	2.0	6.0	8.5	
	0.5	0.5	3.0	6.0	12.7	

FAA CAT I
Sensor Error Limit   4.3

N.C. Narrow Correlator
S.C. Standard Correlator
Mf   Multipath Factor

$$\sigma_v = M_f D_v \sqrt{\sigma_a^2 + \sigma_g^2}$$

V.   AVAILABILITY RESULTS

A.   Data Sets

i.   McMurdo

For this study days 45 to 200 from the McMurdo 1992 set were used.   This included one intense magnet storm at day 131. Extending the set farther was difficult due to the increasing occurrence of data logging errors. Most data logging errors were identifiable because they shared the characteristics that: there were a large number of satellites in track, several satellites went away within 2 seconds, they stayed away 19-22 sec (the system had an error recycle feature), and they all came back together at once with good tracking indicators immediately. It is felt, however, that some data logging errors are still present in the data set.

In addition to the data logging problem, there are real loss of locks at moderate elevation angles that occur every sidereal day and line up with other antenna on the roof. These have been left in the data set. Because no events not clearly due to the experimental equipment have been removed, it is felt that the numbers are conservative and represent an over estimate of the loss of lock rates.

ii. South Pole

The South Pole data was selected from archive tapes loaned to NPS by USGS. Only 120 days were extracted and these contained 117 valid daily data sets. The selection was biased toward times of geomagnetic storms. The intense storm around day 131 was extracted as well as a later storm around day 280.

There were no apparent problems with the data sets and the data were used as extracted with no editing.

B.   Receiver Criteria

The raw measurements are of loss of locks during this experiment. At the time the data was taken the full constellation was not in place. Some method must be used to map these data into receiver functionality in a real landing system in 1995 and beyond. This mapping will depend on the number of channels that the airborne receiver has.   (It is assumed that the ground station will track all in view.)

Two receiver types are considered, a 6 channel receiver that meets the minimum specifications in the MASP and a receiver with 9 or more channels, which will be called an "all in view" receiver here. It will be assumed that any satellite lost would have been

in track by the airborne receiver. Therefore, any loss of a single satellite will cause a 6 channel receiver to loose RAIM satellite isolation ability. Two at once (defined as within 30 sec of each other) will cause it to loose all RAIM capibilities and declare itself non-functional.

For 9 channel or All in View receivers the loss of two satellites will not necessarily cause a loss of functionality. A study was performed using the final constellation and the McMurdo and South Pole sites. This computed the DOP's from all combinations of satellites in view. It then dropped satellites from consideration that caused the worst effect on the VDOP. For Pole the loss of the best two causes the VDOP to go above 6 only for 4 different periods of 5 min periods per day. At McMurdo it is worse for the loss of the best 2. It was decided not to define the loss of two satellites with 30 sec of each other as a loss of functionality for all in view receivers.

However if 3 satellites are lost, it will be assumed that some very large event is in progress and the receiver would drop its error flag. Therefore it was assumed that if three satellites had a loss of lock above 10 deg, an all in view receiver was out of specification.

It should be noted that these conditions will be automatically recognized by airborne receiver meeting the FAA specification. An

error flag will drop if the geometry for the solution puts the error outside the tunnel limits.

C. Raw Long Term Availability Values

The percent of time that a given receiver type was unavailable on a daily basis and over the entire data sets were calculated. These values can be compared to the MASP specification of 98 % availability on a long term basis and continuity of 10^{-4} . However these are values intended for hardware error problems. In this case the effects are outside the receiver. In addition the effects are not randomly distributed. They are dominated by solar eruptions that intersect the earth as indicated by geomagnetic storms. It's a lot like the unavailability of DFW airport in the summer due to a line of thunder storms. In both cases it's not equipment related and there is some warning.

With that disclaimer, the raw daily values of unavailability for McMurdo using an all in view receiver are shown in Fig 9. The dominate event, on day 162, does not correspond to any magnetic activity. Over 5 minutes all satellites, in all parts of the sky are lost and come back. The event is unlikely to be ionospheric scintillations and is likely an equipment problem. However it was included in the unavailability statistics.

31

Unavailability McMurdo
All in View Receiver
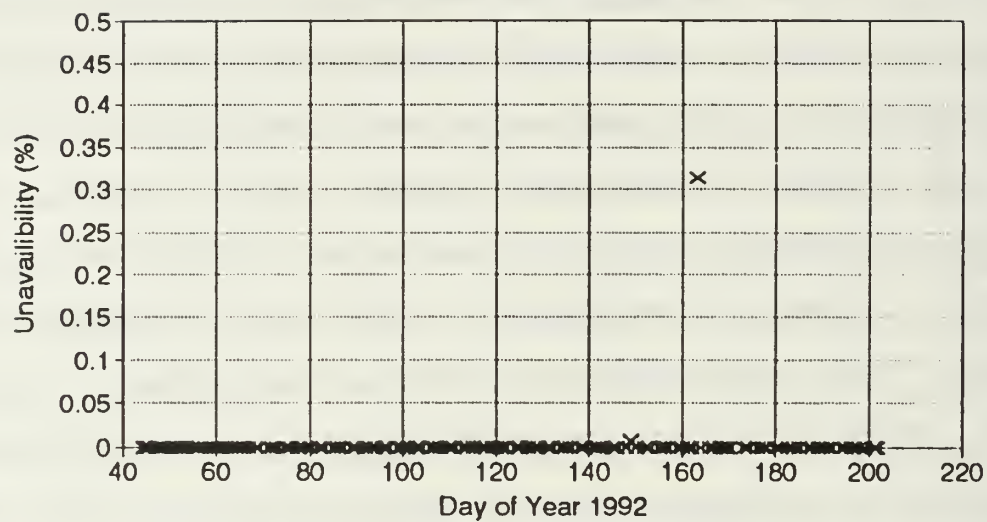
Figure 9

Unavailability McMurdo
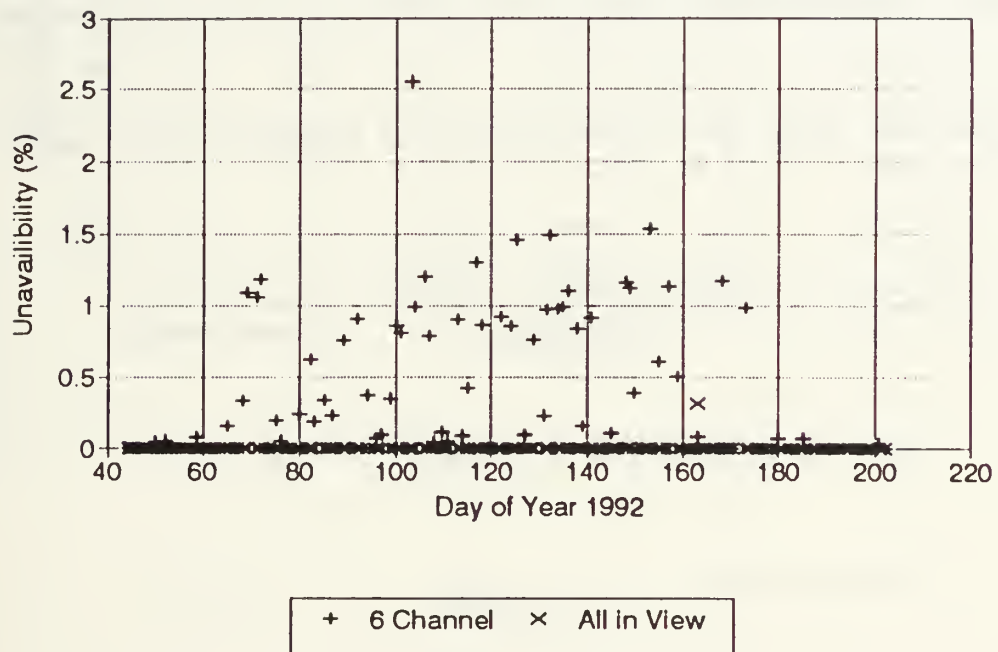## All in View and 6 Channel Receivers

Figure 10

The 6 channel receiver unavailability for McMurdo is given in Fig. 10. This is presented for completeness but is likely filled with un-detected data logger problems.

Both the 6 channel and all in view receiver data for South Pole are presented on Fig. 11. Here there is no known data problem and the events seem related to magnetic activity. It is felt that these events are real and that Pole has a genuine scintillation problem, although one that is not serious for a GPS landing system.

The raw long term unavailability probabilities are:

	McMurdo	South Pole
6 Channels	3×10^{-3}	4×10^{-4}
All in View	7×10^{-5}	5×10^{-5}

D.   Geomagnetic Storm Day 131 1992 (May 10)

It is instructive to examine the data at both sites during the most intense magnetic storm captured. The geomagnetic index Ap is available for each 3 hour period. This three hour Ap is plotted against time in Fig 12 for 5 days beginning at day 130. 1992.

34

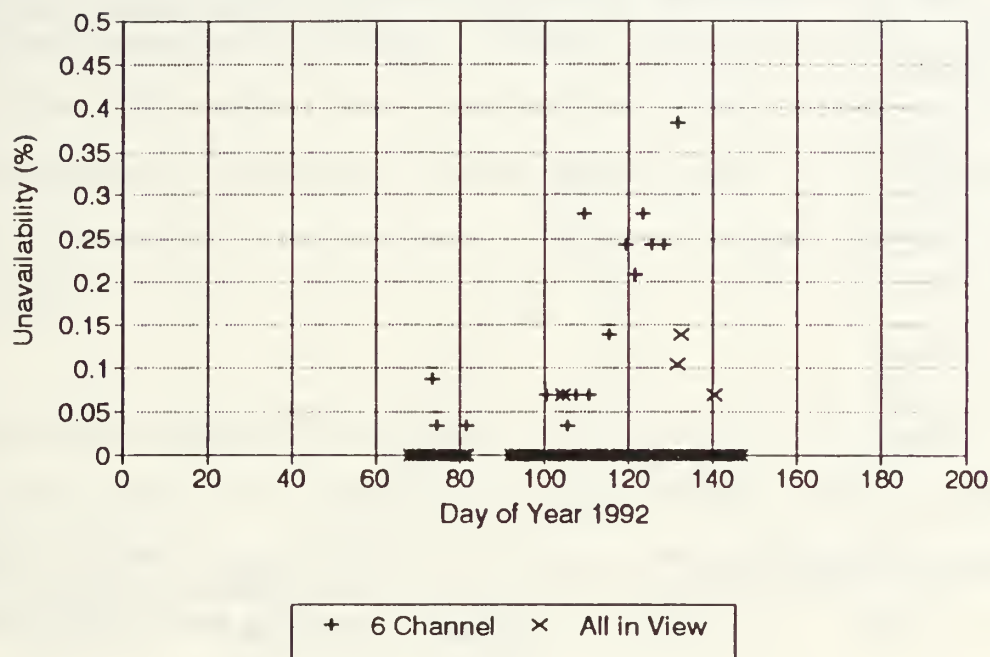## Unavailability South Pole
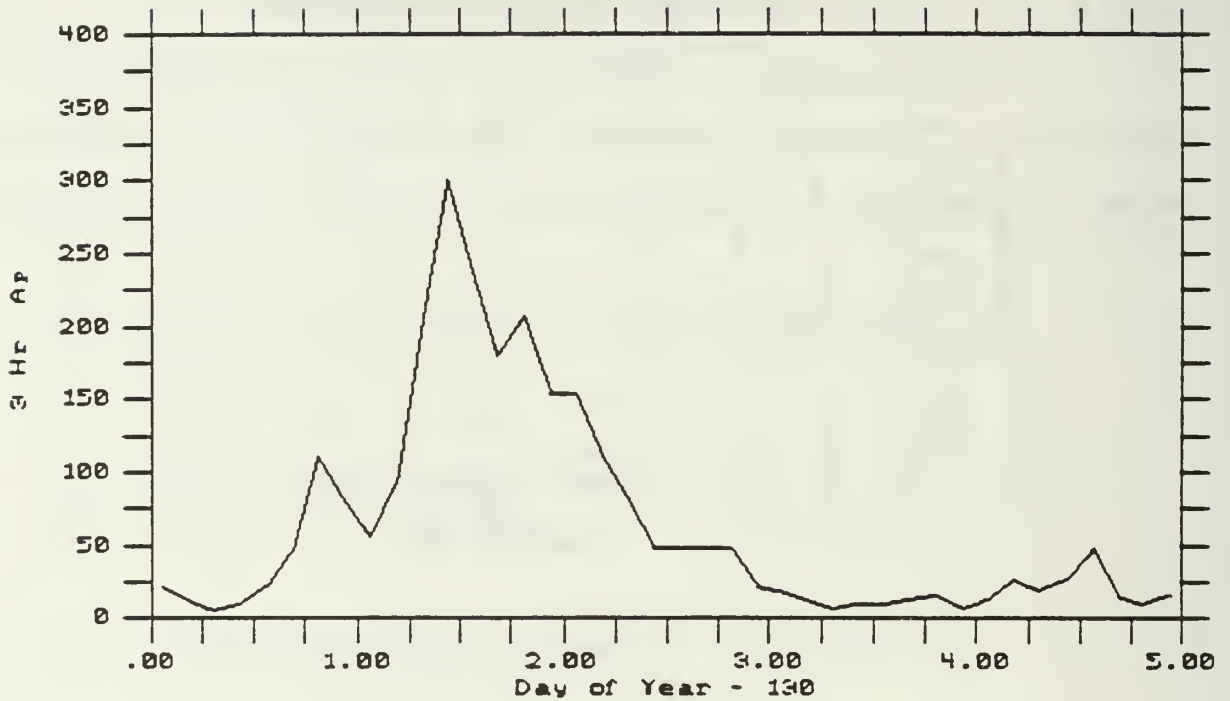### All In View and 6 Channel Receiver

Figure 11

Figure 12
Magnetic Activity During Major
Storm, May 1992

36

There is a peak of over 300 about noon, UT on day 131.

The loss of locks at McMurdo are plotted in Fig 13. Here the vertical axis is the elevation angle of the loss of lock. Several features can be seen on this figure. First there is an intense set of loss of locks that occurs just at the peak of the storm. Clearly the storm has an effect. Second there are a few losses at about 45 deg that appear to be repeating a day later. These are probably local multipath off items on the roof of building 165. Finally the missing data is due to the data logger being off line a that time.

A detailed examination of the data reveals only 3 real events of two satellites out within 30 sec of each other. The two satellite outages lasted from 20 - 60 s. There were no losses of 3 or more satellites at once.

A similar plot for the South Pole data is shown in Fig 14. While it looks similar to the McMurdo data, there are several events where the symbols are so close they do not show as distinct events.

The valid events cover a period of 1.5 hours in two sections. There is an intense period of 20 minutes when there is one loss of 3 satellites for 90 s and 5 losses of two satellites. After one

Figure 13
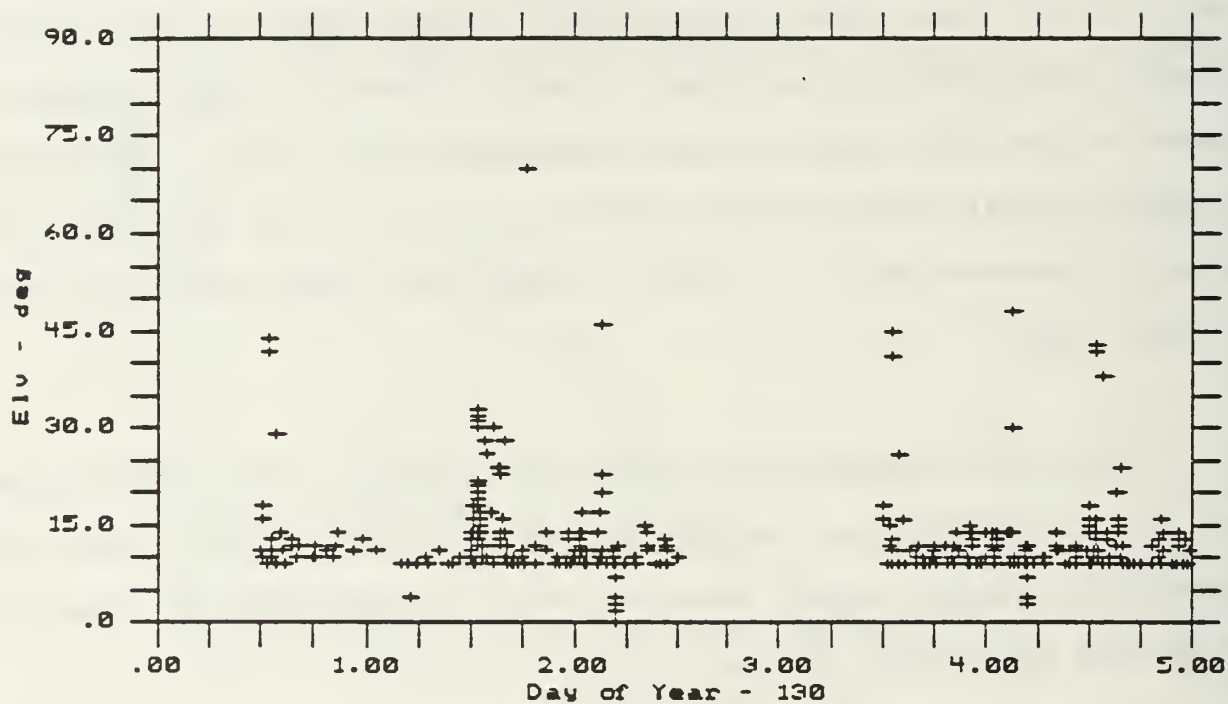Loss of Locks vs Elevation Angle at
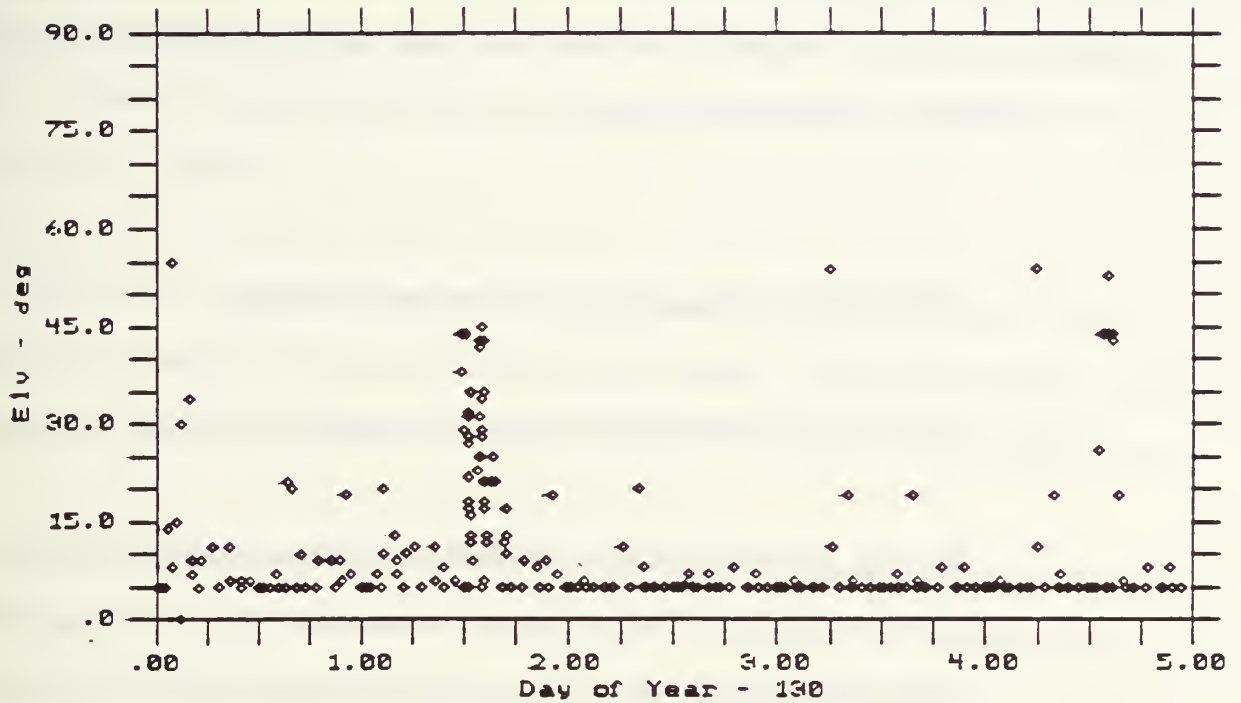McMurdo for May 1992 Magnetic Storm

38

South Pole

Figure 14
Loss of Locks vs Elevation Angle at
South Pole for May 1992 Magnetic
Storm

39

hour of good tracking there are 2 events where 2 satellites are lost over 5 minutes. Even an all in view receiver might drop its error flag a few times during the intense 20 minute period.

It should be noted that there were no 3 satellite loss events during a later more moderate storm at South Pole station. The intensity of the magnetic storm must be on the order of an Ap of 250 to cause these events.

E.   Realistic Assessment of Unavailability

The most valid statements about availability may be that:

During intense storms with Ap greater than 250 South Pole station will likely experience one or two periods of unavailability for an all-in-view receiver with durations about one to two minutes. For 6 channel receivers events over extended times of 30 min are to be expected.

During intense storms at McMurdo all-in-view receivers will likely have no loss of availability, but 6 channel receivers will have a small number of periods lasting 1 to 2 minutes of unavailability.

No very intense storms were captured in the data set. An

40

educated estimate is that South Pole will have one to two periods of 30 min of all in view outages and severe problems for 6 channel receivers.

The problem now comes down to the occurrences of geomagnetic storms of various intensities. During the two peak solar activity years of a solar cycle there are 5 to 10 very intense storms per year. There are one to two extremely intense storms per solar cycle of 11 years.

Ignoring "great" storms, during solar maximum there would be about 10 outages of 2 min at Pole per year. Less than half this rate would occur at McMurdo. This is for all in view receivers.

"Great" storms are predictable about 36 hours in advance from a lot of other prompt events associated with them (X-rays etc.). In fact the biggest problem is a false alarm rate. It's hard to predict if the ejecta from the sun will hit the earth.

VI. RECOMMENDATIONS

Based on the data collected from McMurdo and South Pole the following are recommended with respect to accuracy and scintillation effects using GPS for a landing system in Antarctica:

1. Proceed with GPS Landing Systems,

2. Ground Stations Should Have Narrow Correlator or Equivalent Low Noise Receivers,

3. The Location For the Ground Site Antenna Should Be Very Clean of Multipath Objects,

4. Aircraft Receivers Should Have 9 Or More Channels

5. Aircraft Receivers Should Have Narrow Correlator Receivers Where Practicable

6. Pseudolites Are Not Required If The Ground Site Is Clean And Narrow Correlator Or Equivalent Ground Receivers Are Used.

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